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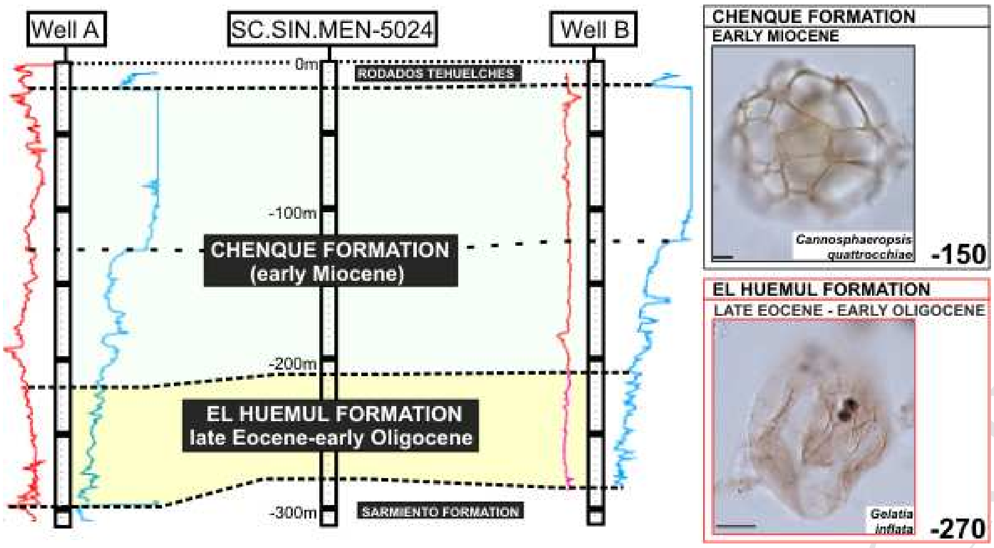

Well A
SC.SIN.MEN-5024
Well B
0m
RODADOS TEHUELCHES
-100m
CHENQUE FORMATION
(early Miocene)
-200m
EL HUEMUL FORMATION
late Eocene-early Oligocene
-300m
SARMIENTO FORMATION
CHENQUE FORMATION
EARLY MIOCENE
Cannosphaeropsis quattrocchiae
-150
EL HUEMUL FORMATION
LATE EOCENE - EARLY OLIGOCENE
Gelatia inflata
-270

A late Eocene-early Oligocene transgressive event in the Golfo San Jorge basin: palynological results and stratigraphic implications

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Abstract: A new Cenozoic dataset in the subsurface of the South Flank of the Golfo San Jorge Basin (Santa Cruz province) allowed to identify a non-previously recognized transgressive event of late Eocene to early Oligocene age. Below of a marine succession containing a dinoflagellate cyst assemblage that characterizes the C/G palynological zone of the Chenque Formation (early Miocene), a 80-110 m thick marine succession contains a palynological assemblage integrated by *Gelatia inflata, Diphyes colligerum* and *Reticulatosphaera actinocoronata* supporting the occurrence of a marine incursion in the basin during the Eocene-Oligocene transition (EOT). The new lithostratigraphic unit - here defined as El Huemul Formation – covers in sharp contact to the Sarmiento Formation, and become thinner from East to West; the unit has been identified in about 1,800 well logs covering up to 3,500 km^2, and its subsurface distribution exceed the boundaries of the study area. The El Huemul Formation consists of a thin lag of glauconitic sandstones with fining-upward log motif, followed by a mudstone-dominated succession that coarsening-upward to sandstones, evidencing a full T-R cycle. Preservation of the El Huemul Formation in the subsurface of the South Flank has been favored by the reactivation of WNW-ESE late Cretaceous normal faults, and by the generation of N-S striking normal faults of Paleocene-Eocene age. Flexural loading associated to igneous intrusions of Paleocene?- middle Eocene age also promoted the increase of subsidence in the South Flank of the basin prior to the transgression.

Keywords: El Huemul Formation, pre-Patagoniense transgression, late Eocene to early Oligocene dinoflagellate cysts, Golfo San Jorge Basin, Patagonia.

1. Introduction

The Eocene-Oligocene stratigraphy of the Golfo San Jorge Basin has been assigned to the Sarmiento Formation (middle Eocene-early Miocene), a terrestrial pyroclastic succession widely distributed in Patagonia (Simpson, 1940; Feruglio, 1949; Spalletti and Mazzoni, 1979; Mazzoni, 1985; Bellosi *et al.*, 2002; Bellosi and Madden, 2005; Bellosi, 2005) that contain the most complete fossil mammal succession of Southern South America (Pascual and Odreman Rivas, 1973; Marshall *et al.,* 1977; Marshall and Pascual, 1978; Marshall *et al.,* 1986; Legarreta and Uliana, 1994) and a well-calibrated chronostratigraphy (Re et al., 2010; Dunn et al., 2013). The Sarmiento Formation in some sections that outcrop in the North Flank of the Golfo San Jorge Basin **(Fig. 1)** underlies the Chenque Formation (Bellosi, 1990a), the local name assigned to a more-widely distributed, and diachronic geological event known as the "Patagoniense" transgression (Windhausen, 1924; Frenguelli, 1929, Feruglio, 1949; Legarreta *et al.*, 1990; Malumián and Nañez, 2011). The Chenque Formation is a 350-450 m thick marine unit that comprises five shallowing upward depositional sequences recording open marine, shallow water and storm-dominated marine environments in the lower half of the unit, and tide-dominated, estuarine or lagoonal environments toward the top of the unit (Bellosi, 1990a,b, 1995; Bellosi and Barreda, 1993; Paredes, 2002); its age is early Miocene supported by palynological studies (Bellosi and Barreda, 1993; Barreda and Palamarczuk, 2000). In the nearby Austral Basin of southern Santa Cruz several marine lithostratigraphic units identified as part of the "Patagoniense" transgression were also defined: San Julián and Monte León Formations (Bertels, 1970; Panza *et al.* 1995) with ages of 25-23 and 22-18 ma. respectively (Parras et al., 2012), the Estancia 25 de Mayo Formation with ages of 20-19 ma. (Cuitiño et al., 2010, 2014) and the

El Chacay Formation (Chiesa and Camacho, 1995). A latest Eocene to early Oligocene transgression in the Austral Basin is represented by the uppermost part of the Río Turbio Formation in the southwest of Santa Cruz province (González Estebenet, 2015) and also by the upper member of the Cerro Colorado Formation, named CCD member (Olivero and Malumián, 1999; Malumián and Olivero, 2006) and synchronic units (Cabo Peña Formation) cropping out in the northern part of Tierra del Fuego (Guerstein et al., 2008). Although the stratigraphy of the Sarmiento and Chenque formations in the North Flank of the basin is well known, its stratigraphy in the subsurface of the South Flank or westward of the San Bernardo Fold Belt remains poorly studied, with sparse published data (Cardinali *et al.*, 2000; Paredes *et al.*, 2006).

In this paper, we present evidence of the occurrence of a non-previously recognized transgressive event underlying the Chenque Formation of the Golfo San Jorge basin, currently preserved in the subsurface of the basin. The aims of this article are a) to characterize the internal stratigraphy of the mid Cenozoic marine succession in the subsurface of the South Flank of the basin, b) to document new biostratigraphic information based on the palynological assemblages from the marine lithostratigraphic units, and c) to discuss their integration into the sedimentary evolution of the Golfo San Jorge Basin.

1.1. Geological setting

During the latest Cretaceous and the Cenozoic, the Golfo San Jorge Basin developed as a wide depositional area with low tectonic subsidence. The accommodation was generated mainly by sea-level fluctuations and extensional tectonics (Fossa-Mancini, 1932; Uliana and Biddle, 1987; Legarreta *et al*., 1990; Giacosa *et al*., 2004; Foix *et al*., 2008, 2012a).

Coeval with a global highstand stage (Haq *et al.*, 1987) recorded in a number of Southwestern Atlantic Ocean basins during the Late Cretaceous and Danian, an Atlantic marine transgression flooded the Golfo San Jorge Basin. The preserved rocks correspond to the Salamanca Formation (Ihering, 1907; Lesta and Ferello, 1972) and represent shelf, estuarine and deltaic environments (Matheos *et al.*, 2001; Iglesias *et al.*, 2007; Foix *et al.*, 2008, 2012b; Clyde *et al.*, 2014) covering the continental succession of the Cretaceous Chubut Group (Lesta, 1968; Lesta and Ferello, 1972).

SUGGESTED LOCATION OF FIGURE 1

From the late Danian to the Thanetian, transitional and shallow marine environments (Legarreta *et al.*, 1994) evolved to high-sinuosity fluvial deposits with paleosols (Andreis *et al.*, 1975) known as Río Chico Formation (Marshall *et al.*, 1977, 1983; Foix *et al.*, 2013) or Río Chico Group (Bellosi and Madden, 2005; Raijemborn *et al.*, 2010). Towards the inner part of the basin, facies of this unit are laterally related to pyroclastic events with palaeosols development (Tobas de Koluel Kaike) (Krause *et al.*, 2010).

From the middle Eocene to the early Miocene extensive tuffaceous deposits known as Sarmiento Formation or Group were deposited in a low-gradient continental setting (Ameghino, 1906; Windhausen, 1924; Feruglio, 1938; Ardolino *et al.*, 1999). These deposits represent distal products of the Andean Magmatic Arc activity and their reworking by fluvial and aeolian systems. Their wide distribution and abundant mastological content as well as numerous internal unconformities showing replacement of faunal associations have allowed us to produce a subdivision with chronostratigraphic value, defining different "Land Mammal Ages" (Simpson, 1940, 1948, 1967; Marshall *et al*., 1983, 1986; Bellosi, 2005), which are commonly used as a reference chart in South America (Dunn *et al.*, 2013). Coeval with the deposition of the Sarmiento Formation there are alkaline intrusive rocks elsewhere in the basin (Ferello, 1969; Bitschene *et al.,* 1991; Chelotti *et al.,* 1996) and minor volcaniclastic deposits (Paredes *et al.*, 2008). The ages of the intrusive rocks could be grouped into a late Eocene event (35-34 Ma) and an Oligocene event (29-25 Ma) (Ardolino *et al.,* 1999).

The Chenque Formation (Bellosi, 1990a), was deposited over the Sarmiento Formation or Río Chico Group. This unit is in part coeval with the upper section of the Sarmiento Formation (Colhuehuapense Member), deposited in a deep incised valley (Bellosi *et al.,* 2002). The palynological analysis of the Chenque Formation indicates an early to-Middle Miocene age (Barreda and Palamarczuk, 2000). These marine sediments grade to high-sinuosity fluvial and aeolian deposits, known as Santa Cruz Formation or "*Santacruciano*" (Ameghino, 1898; Feruglio, 1949; Lesta et al., 1980), which has been assigned, according to radimetrical ages, to the Burdigalian-Langhian interval (Feagle *et al.*, 1995; Marshall *et al.,* 1986). In the South Flank of the basin there are no records of the Santa Cruz Formation. Since the Middle Miocene the Golfo San Jorge Basin has been subjected to an erosive regime related to the elevation of the Andean Ranges and to an overall fall in the sea level. The "Rodados Tehuelches" constitute high-energy fluvial systems associated with the melting of extensive glaciations during the Pliocene and Pleistocene.

1.2. Study area

The Golfo San Jorge Basin has been divided according to its structural style (Figari *et al.*, 1999) into five major regions. Three of these regions are in the Eastern Sector of the Basin (North Flank, Centre of Basin and South Flank), where an extensional style prevails (Giacosa *et al.*, 2004; Foix *et al.*, 2008). West of this area, is the San Bernardo Fold Belt, which has a NNW-SSE orientation and which rose up mainly during Neogene times (Peroni et al., 1995). The fifth region, called the Western Sector, is located further west of the Fold Belt and is dominated by extensional structures (Clavijo, 1986), or with little evidence of positive tectonic inversion (Figari *et al*., 1996).

The study area is geographically located in the Santa Cruz province and covers an area up to 3,500 km^2 **(Fig. 1, 2).** With exception of the westernmost part, where no Cenozoic sediments are preserved due to uplift of the fold belt, most of the study area lies in the South Flank of the Basin, which is characterized by moderate rates of subsidence and WNW-ESE to W-E striking normal faults that mostly dip toward the N. The main depocentre of the basin is located northward of the study area, where the Cenozoic sedimentary succession is up to 900 meters thick (Legarreta and Uliana, 1994). Although no detailed paleogeographical scenarios has been carried out in the subsurface of the South Flank, the regional reconstructions of the marine Salamanca and Chenque Formations consider the study area as the southern side of a large W-E engulfment open to the Atlantic Ocean (Bellosi, 1995; Malumián et al., 1999; Malumián and Nañez, 2011)

2. Methodology

The main stratigraphical boundaries of the Cenozoic record were established primarily in mud-logging descriptions of 20 wells distributed throughout the study area; the description focused on the identification of the dominant lithology and grain size, clast types and glauconite grains, and fossil content (molusks, bivalves among others). Once established the main lithostratigraphic units, we focused in defining the internal boundaries of the marine succession of mid-Cenozoic age by using mud-logging description of each well and the available well logs; typical well log data consisted of total gamma ray, resistivity and spontaneous potential. More than 1,800 well logs were available for this study, and were confidently correlated across up to 3,500 km^2. A grid of four semi-regional cross sections was constructed across the study area **(**see **Fig. 2)**. Three main depositional cycles could be defined in the marine record that overlies the Sarmiento Formation, informally defined as Cycle I to III in ascending order **(Figs. 2** and **3)**.

Thirteen samples of the well SC.SIN.MEN-5024 **(Fig. 2)** were processed for palynological analysis, eleven of which proved to be palynologically productive. Due to the nature of the samples (cuttings), we usually use the upper occurrence of the taxa and barely used the lower occurrences. The physico-chemical procedures included hydrofluoric and hydrochloric acid treatments. The organic fraction was sieved through screens of 10 and 25 µm and mounted in glycerine jelly.

Light microscopic examination was undertaken using a Nikon Eclipse 600 microscope with an attached Micrometrics digital camera. The illustrated specimens are defined in the plate captions by the sample and slide number followed by the England Finder (EF) references. The studied slides are housed in the collection of the Laboratorio de Palinología - INGEOSUR at the Universidad Nacional del Sur, Bahía Blanca, Argentina.

The dinoflagellate nomenclature follows Fensome *et al.* (2008) unless otherwise indicated. The timescale used in this work is the Geological Timescale proposed by Gradstein *et al.* (2012).

SUGGESTED LOCATION OF FIGURE 2

3. Mid-Cenozoic marine record in the South Flank

In the subsurface of the South Flank of the Golfo San Jorge Basin the mid-Cenozoic marine sedimentation overlies in sharp contact tuffaceous strata of the continental Sarmiento Formation. However, in some places of the western part of the study area the Sarmiento Formation is fully eroded and the marine record directly overlies the continental Río Chico Group. The detailed relationship with the underlying substrate was not systematically mapped due to the complex differentiation among the Sarmiento and Río Chico groups using well logs or mud logging samples.

3.a. Internal organization

Based in lithology, grain size trend, well log motifs and color changes, the mid-Cenozoic marine succession of the study area can be internally subdivided into three major sub-units (**Fig. 3**).

The base of the lowermost unit, herein named Cycle I, is identified by abrupt superposition of a 10-20 m thick package of pale-green, fine, glauconitic sandstones with fining upward log motif on white-to-yellow tuffaceous deposits of the Sarmiento Formation **(Fig. 4)**; broken shells of marine origin are also commonly found in this basal interval. Cycle I typically reach 80-110 m of thickness; most of this cycle consists of pale green or grey mudstones with serrate log character that vertically evolves to interbedded sandstones and mudstones with a slightly coarsening-upward log signature (**Fig. 3**). The sandstone-dominated package at the base of the Cycle I can be up to 20 m thick, and has been deposited in a shallow marine (shoreface) environment evolving upward to inner-shelf environment; the overall fining-upward log motif of this basal section signifies a landward migration of the coastline during a transgressive system tract (Cattaneo and Steel, 2003). The lack of significant relief at the base, inferred by gradual thickness variation at regional scale of the sandstone package, suggests that the basal sequence boundary is not associated to incised valley fills (Catuneanu, 2006). Upward in the sedimentary pile, a coarsening upward package that reach up to 90 m thick complete the Cycle I, reflecting a dominant seaward shift of facies and environments consistent with the development of a highstand system tract, which volumetrically dominates the depositional sequence (Posamentier and Allen, 1999). The fining-upward to coarsening-upward internal organization of this cycle is well represented in the eastern part of the study area (**Fig. 3)** and can be followed for tens of kilometers in all directions; although in some cases the basal coarse-grained sandstones can be absent and the uppermost sandstones can be either amalgamated or absent, hampering their correlation throughout the study area.

The lower boundary of the Cycle II is also erosional and can be considered as a sequence boundary, overlying the preceding coarsening-upward trend or muddy facies of the top of the Cycle I. This cycle commonly displays three sub-units: the two lowermost sub-units are represented by interbedded glauconitic sandstones and pale green mudstones with thickness between 30-50 m. The lower sub-unit can be correlated across most of the study area and likely represent a transgressive system tract; the overlying sub-unit display a coarsening upward trend and is interpreted as a highstand system tract. The uppermost sub-unit of the

Cycle II is 35-45 m thick and is characterized by a mudstone-dominated, coarsening upward log motif, which reflects the sediment starvation in the inner shelf environment evolving upward to a lower shoreface setting or to a transition to off-shore environment. Although no direct data are available, their log signature is comparable to those observed in outcropping sections of the Chenque Formation in the North Flank (Paredes, 2002), where the finer packages represent inner shelf environments and the glauconitic sandstones are associated to a lower shoreface environment.

Cycle III typically consists of conglomerates and glauconitic sandstones that reach thickness up to 130 meters. This cycle is easily identified in mud-logging records and also using well logs (**Fig. 4)** because of the distinctive blocky signature in resistivity and conductivity profiles, its base represent a sequence boundary that can be traced across the entire study area. The sandstone-rich package is vertically interrupted by two or three thin intervals of interbedded mudstones and sandstones with slightly serrated log motif. The log-signature is in part due to the occurrence of fresh-water hosted in the pore space of the sandstones, making this sandstone interval a major aquifer reservoir in the basin. This sandstone-rich package can be found elsewhere in the study area, reflecting widespread deposition of sandstones in shoreface conditions, comparable to the littoral sandbar complexes observed in the Chenque Formation in the North Flank of the basin (Bellosi, 1996, 2000). The homogeneous nature of the cycle III prevent the reliable identification of distinctive stacking patterns that could be useful to interpret transgressive or highstand system tracts.

SUGGESTED LOCATION OF FIGURE 3

SUGGESTED LOCATION OF FIGURE 4

3.b. Palynological record

Palynological assemblages

The palynological organic matter recovered from the well SC.SIN.MEN-5024 **(Fig. 4)** is mainly composed by phytoclasts, amorphous organic matter and palynomorphs. Particularly, palynomorphs are represented by dinoflagellate cysts, pollen, spores, prasinophycean algae and organic linings of foraminifera. Dinoflagellate cyst assemblages are generally low diverse and moderately well-preserved. The uppermost part of the sampled interval (Cycle II), between 150 and 210 meters depth, are dominated by gonyaulacacean cysts, especially species of *Spiniferites* and *Operculodinium* **(Fig. 5)**. The palynological assemblage recovered from the 195 meters depth is characterized by high proportions of prasinophycean algae (*Tasmanites* sp.). The assemblages from the lower sampled interval (between 240 and 270 meters depth) are mainly composed by *Reticulatosphaera actinocoronata*, protoperidiniacean cysts (*Lejeunecysta* spp. and *Selenopemphix* spp.), species of *Spiniferites*, *Operculodinium* and *Lingulodinium* **(Fig. 6)**. These lower palynological samples contain abundant amorphous organic matter and linings of foraminifera. Both stratigraphic intervals are separated by a level at 225 meters depth with scarce marine dinoflagellate cysts showing an increase of continental palynomorphs, which can be related to a regressive episode. Most of the marine identified taxa are illustrated in **Figure 5** and **Figure 6,** and their stratigraphic distribution are shown in **Table I**.

SUGGESTED LOCATION OF TABLE I

Dinoflagellate cyst biostratigraphy

Four pollen and dinoflagellate cyst assemblage zones have been previously recognized in the Chenque Formation of the Golfo San Jorge Basin (Barreda and Palamarczuk, 2000). These are: 1–(M-M/R) *Mutisiapollis viteauensis – Margocolporites tenuireticulatus / Reticulatosphaera actinocoronata* (Late Oligocene, Chattian), 2– (C-T/L) *Cyperaceaepollis neogenicus – Tricolpites trioblatus / Lingulodinium hemicystum* (Early Miocene, early Aquitanian), 3– (G/C) *Glencopollis ornatus / Cannosphaeropsis quattrocchiae* (as *C. utinensis*) (early Miocene, late Aquitanian), and 4– (T-B/H) *Tubulifloridites antipodica – Baumannipollis chubutensis / Hystrichosphaeropsis obscura* (Early Miocene, Burdigalian). The lowermost zone was recognized in coastal outcrops located southeastward of the study area. The other zones were identified in the North Flank of the Golfo San Jorge basin (Barreda and Palamarczuk, 2000).

The distribution of the dinoflagellate cysts in the well SC.SIN.MEN-5024-B allows us to differentiate two stratigraphical intervals in agreement with the lithological data and the well log signature. Because of the nature of the samples (cuttings), we usually use the upper occurrence of the taxa and barely used the lower occurrences. The dinoflagellate events recorded in both intervals constrain the minimal ages of each part of the section. In the uppermost part (Cycle II), between 150 and 210 meters depth, the presence of *Cannosphaeropsis quattrocchiae* suggests an age no younger than early Miocene (Guerstein *et al.*, 2001). The stratigraphical distribution of this species is consistent throughout the different Southwestern Atlantic basins (Barreda and Palamarczuk, 2000; Guler and Guerstein, 2002; Premaor et al., 2013). The records of *C. quattrocchiae* in outcropping sections of the eastern part of the Austral and Golfo San Jorge basins indicate that this species has a short biochron related to the Burdigalian, between 17.5 and 18.5 Ma (Parras *et al.*, 2012; Perez Panera *et al.*, 2014). The biochrons of other taxa identified in this stratigraphic interval are consistent with this age (e.g. *Dapsilidinium pseudocolligerum*, *Hystricokolpoma rigaudiae*, *Melitasphaeridium* cf. *choanophorum*, among others).

This stratigraphical interval that represents the Cycle II bears dinoflagellate cyst assemblages typical of the “*Patagoniense*” transgression, which have been previously recognized in different Southern-western Atlantic basins. The assemblages analyzed herein are equivalent to the G/C assemblage zone recovered from the Chenque Formation in outcrops of the Golfo San Jorge Basin and along the coast of the South Flank (Barreda and Palamarczuk, 2000). Our assemblages resemble those from the Austral Basin, from both the Estancia 25 de Mayo Formation (Guerstein *et al.*, 2004) and Monte León Formation in its type area (Barreda and Palamarczuk, 2000; Perez Panera *et al.*, 2014) and also were consistently recorded in five offshore wells drilled in the Colorado Basin (Guler and Guerstein, 2002; Guerstein *et al.*, 2010).

SUGGESTED LOCATION OF FIGURE 5

In Cycle I, between 240 and 300 metres depth, *Gelatia inflata*, *Spiniferites scalenus*, *Nematosphaeropsis* sp. A, *Diphyes colligerum* and *Tuberculodinium* sp. (of Guerstein et al., 2008) as well as *Reticulatosphaera actinocoronata* (**Fig. 6**) suggest a late Eocene to early Oligocene age. The records of *Gelatia inflata* in the Southern Hemisphere are constrained to the late Eocene - early Oligocene (Guerstein *et al*., 2008) with a calibrated first occurrence at 35.4 Ma (Brinkhuis *et al.*, 2003; site 1172 on the Tasman Plateau and Guerstein pers. obs.; site 511 on the Malvinas Plateau). Likewise, the first occurrence of *Reticulatosphaera actinocoronata* at 33.5 Ma (Brinkhuis *et al.*, 2003), together with the last occurrence of *Diphyes colligerum* at 33.3 Ma (Williams *et al.*, 2004) restrict the age of these assemblages to the Eocene – Oligocene Transition (EOT). The presence of *Tuberculodinium* sp. of Guestein *et al*. (2008) at 255 meters depth reinforces this biostratigraphical interpretation for the lower interval of the section. Up to now, this species of *Tuberculodinium* seems to be endemic to the southern basins of Argentina and has been only recorded in units considered to be no younger than early Oligocene, both in the Austral Basin (Guestein et al., 2008) and in the Ñirihuau Basin (Asensio *et al.,* 2010). The samples from the Cycle I contain also *Nematosphaeropsis* sp. A, recognized by González Estebenet (2015) at the uppermost part of the Río Turbio Formation in Santa Cruz province. The age of the uppermost part of this unit was interpreted as late Eocene. Our assemblages bear also species recorded at the Site 511 on the Malvinas Plateau (Goodman and Ford, 1983; Houben *et al.,* 2011). All the units mentioned above have been deposited as the result of the transgressive event that occurred around the EOT.

SUGGESTED LOCATION OF FIGURE 6

3.c. Regional distribution patterns

The above mentioned stacking pattern that record the Cycle I evidence a full transgressive-regressive depositional sequence bounded by erosional surfaces, with occurrence of glauconite grains and broken shells of marine affinity. The ages provided by the dinoflagellate content of Cycle I has proved the preservation in the subsurface of rocks related to a transgressive event up to 10 millions of years older than the age assigned to the overlying Chenque Formation, supporting the definition of a new lithostratigrafical unit (Paredes et al., 2014). The El Huemul Formation (*nov. denom.*) is, until now, a subsurface unit preserved in the South Flank of the Golfo San Jorge Basin underlying the Chenque Formation, and overlying terrestrial strata of the Sarmiento Formation. The El Huemul Formation is temporally equivalent to the Vera Member of the Sarmiento Formation (Re et al., 2010; Dunn et al., 2013), preserved in the North Flank of the Golfo San Jorge Basin. Its type locality is here established in the Meseta Espinosa oilfield (location in **Fig. 2**), where typical well logs of the unit are as those shown in **Figure 3**.

Three north-south stratigraphical cross-sections (**Fig. 7)** were constructed to illustrate the regional correlation of the marine succession, and its lithostratigraphical units. Using this regional cross sections and wireline logs, structural and isopach maps of both the Chenque and El Huemul formations were created **(Figs. 8** and **9)**, using up to 1,800 well logs that cover an area up to 3,500 km^2. The palynological content of the Cycle I in the subsurface of the study area has demonstrated the occurrence of a non-previously recognized lithostratigraphical unit, herein defined as the El Huemul Formation.

LOCATION OF FIGURE 7

Both the B-B´ and C-C´ cross-sections **(Fig. 7)** show evidence of Cenozoic extensional tectonics with significant displacement of the base of the El Huemul Formation and underlying Cenozoic lithostratigraphical horizons, evidencing the occurrence of extensional reactivation of Cretaceous faults or the generation of discrete population of faults in the Cenozoic sedimentary succession. As a result, the entire Cenozoic succession increases its thickness toward the northern part of the study area. The thickness distribution of the El Huemul Formation **(Fig. 8B)** evidences that the main depocenter was located in the NE part of the study area, with gradual thickness variation following WNW-ESE and NNW-SSE trends; the former orientation is coincident with the strike of the main Cretaceous faults in the South Flank (Fitzgerald *et al.*, 1990; Figari *et al.*, 1999; Chelotti and Homovc, 1998) and the later trend is associated with the orientation of Paleogene normal faults (see below). The El Huemul Formation was deposited over an area exceeding the study area, with erosional boundaries toward the south and west **(Fig. 8B)**. However, as the maximum thickness of the unit is preserved toward the north and northeast of the study area, the unit must be also preserved in the Center of Basin, although it did not reach the North Flank, implying increase of the subsidence rate of the South Flank during the late Eocene-early Oligocene in comparison with the North Flank of the Golfo San Jorge Basin.

The pattern of gradual thinning of both the Chenque and Huemul formations towards the southern basin boundary is modified in the westernmost part of the study area (**Fig. 8B**). The base of the marine sequence (El Huemul Formation?) can be well established there using mud-logging descriptions, and can be easily correlated. It should be mentioned that until now, there is no palynological data of these marine sequences, and the typical log motif of the El Huemul and Chenque formations of eastern areas is not here recognized (compare **Figs. 7A** and **7C**). However, by analyzing the thickness variation of both units, we have tentatively assigned the record to both lithostratigraphical units. **Figure 7C** shows a lower unit with layer-cake distribution (interpreted as the El Huemul Formation), and an upper unit that increases its preserved thickness to the south (interpreted as the Chenque Formation). Further studies in the near future will bring support to the lithostratigraphical assignation, here just inferred by mapping criteria. However, independently of the age of the involved sequences of the marine units in the western region, the increasing of thickness toward the southwestern part of the study area evidences the local creation of a mid-Cenozoic depocentre. In this sense, the structure map of the base of the El Huemul Formation **(Fig. 8A)** shows the occurrence of two N-S striking, near symmetrical depocentres in the western part of the study area. Although the seismic survey of the area does not have adequate vertical resolution at these depths and no N-S faults has been identified, its N-S orientation likely reflects sub-seismic normal faults associated to extensional tectonics during stages of reduced compressional deformation in the fold belt (see Discussion).

SUGGESTED LOCATION OF FIGURE 8

The structural map of the base of the Chenque Formation (lower Miocene) shows a variation in the contour lines **(Fig. 9A)**; to the west the contour lines are NW-SE oriented, and they tend to shift to N-S in the central part of the area, being roughly NW-SE in the easternmost sector. This pattern is similar to those observed in the underlying El Huemul Formation (**Fig. 8A)**, and it is evidencing the location of the main tectonic features in the Cenozoic sedimentary section. The available well data and topography of the study area indicate that the basal contact with the underlying El Huemul Formation is found in the subsurface with no onshore exposures. The analysis of the thickness distribution of the Chenque Formation provides limited genetic information due to the post-Miocene erosion of the unit.

SUGGESTED LOCATION OF FIGURE 9

4. Discussions: Controls on the sedimentation

4.1. Tectonics

During the Paleogene, there was a coexistence of two contrasting tectonic scenarios in the Golfo San Jorge Basin. On one hand, the San Bernardo fold belt became a positive relief (Homovc *et al.*, 1995; Peroni *et al.*, 1995) that limited the westward advance of the

Salamanca Formation in the early Paleocene (Foix *et al.*, 2012b), and the overlying Río Chico Group (upper Paleocene-Middle Eocene) shows important thickness variations along the axis of N-S anticlines segmented by transversal faults. These changes were associated to variations in the degree of inversion and erosion after uplifting of anticlines (e.g. cerro Piedra anticline, Paredes et al., 2006). On the other hand, the Eastern Sector of the basin behaved as a passive margin (Legarreta and Uliana, 1994) characterized by several distinctive phases of extensional tectonics that affect the Salamanca and Río Chico formations (Foix *et al.*, 2008; 2012a) and that continued during the deposition of the early Miocene Chenque Formation (Giacosa et al., 2004). The extensional scenario during the Oligocene was associated with an intraplate alkali basaltic volcanism distributed in most of the basin (Re *et al.*, 2010), and with the formation of N-NW oriented grabens and half-grabens with up to 15 m of throw (Flores, 1954 in Bellosi (1995).

The occurrence of a marine lithostratigraphic unit of late Eocene - early Oligocene age (El Huemul Formation) in the subsurface of the South Flank evidences that the southern margin of the basin was affected by a transgressive event not recorded in the North Flank. The El Huemul Formation can be correlated confidently throughout most of the study area, and consequently, the age of the underlying Sarmiento Formation, which in the subsurface reaches locally up to 210 m thick, cannot be younger than late Eocene. Although there are some uncertainties in the precise location of the base of the Sarmiento Formation using mud-logging descriptions due to lithological similarities with pyroclastic levels of the underlying Río Chico Group, there is clear evidence of the occurrence of an extensional tectonic phase prior to the deposition of the El Huemul Formation **(Fig. 10C)**. Normal faults affecting the Cenozoic sedimentary section show several orientations, but many of them are NW-SE to NNW-SSE oriented, with throws in the Sarmiento Formation exceeding up to 60 meters and reducing its throw downward. In this case thickness variations of the Sarmiento Formation across fault planes are up to 40 meters, supporting syn-sedimentary fault activity during its deposition. Both syn-sedimentary fault activity, as well as reactivation of Paleocene faults has favored the increase of the accommodation space in the South Flank of the basin, producing in turn, a lowland area that was prone to be transgressed during the late Eocene-early Oligocene.

SUGGESTED LOCATION OF FIGURE 10

4.2. Volcanism

Outcropping and sub-surficial igneous rocks in the Golfo San Jorge Basin occurred as necks, sills, lopoliths and laccolites (Vietto and Bitschene, 1994; Vietto, 2000; Menegatti *et al.,* 2014), and associated dykes, with scarce volcaniclastic deposits (Paredes et al., 2008). The emplacement of intrusive and sub-volcanic rocks, made up of basic alkaline magma, was associated with extensional processes linked to mantle upwelling emplaced at different subsurface levels, including all the units of the Cretaceous Chubut Group and the Sarmiento Formation (Bitschene *et al.*, 1991). In the study area, there are several tens of sills up to 1 km^2 in diameter that were sourced by vertical conduits, with distinctive patterns of dykes (**Fig. 11.A**). Chelotti *et al.* (1996) considered that the emplacement of the sub-intrusive bodies was related to the extensional reactivation of WNW-ESE trending normal faults in the late Paleogene, although in several cases, N-S normal faults of Cenozoic age were used as conduct for the emplacement of dykes or as tectonic depressions in which the intrusive rocks were injected. The accumulation of large volumes of basaltic magma in the upper crust constitutes a supracortical load that should have favored the subsidence creation after cooling (Allen and Allen, 2005). Isotopic analysis on exhumed intrusive rocks located south of the Deseado river provided K-Ar ages on whole-rock samples of 55+/-2 Ma (early Eocene) (Cobos and Panza, 2003). However, other correlatable alkaline rocks in the Deseado region were dated as 39 +/- 5 Ma (Panza, 1982) and thin basaltic rocks south of the Pico Truncado locality indicated an age between 33 to 27 Ma (Marshall *et al.*, 1977; Marshall and Pascual, 1978). All these ages are slightly older than those obtained on rocks from the North Flank of the basin (Ardolino *et al.*, 1999), where igneous activity was important during the Oligocene and continued until the early Miocene (Re *et al.*, 2010). The dinoflagellate cyst assemblages constrain the age of the El Huemul Formation to the Eocene-Oligocene transition (EOT), and our subsurface observations and available mud-logging descriptions confirm that the El Huemul Formation was not intruded by the basic alkaline magma, being common that their components can be found as clasts at its base. Based on these data, there is no evidence of igneous activity younger than the EOT, at least in the subsurface of the study area. An implication obtained from the age of the El Huemul Formation in this area is that intraplate volcanism appears to be mainly of pre late-Eocene age in the South Flank, and Oligocene-Miocene in the North Flank. This age distribution is in agreement with the previously observed set of ages presented by Ardolino *et al.* (1999). If volcanic activity reduced in the South Flank prior to the transgressive event responsible for the deposition of the El Huemul Formation, it is likely that the increase in the accommodation space associated to crustal loading and cooling of the igneous rocks have favored the transgression. Flexural isostatic subsidence linked to intracortical loads has been proved to be an important subsidence mechanism in other peri-volcanic basins (Bahlburg and Furlong, 1996; Watts, 2001; Martina *et al.*, 2006), increasing the mechanical subsidence associated to coeval extensional tectonics (Smith *et al.*, 2002). Further studies, out of the scope of this work, should bring new insights into the links between the igneous activity and the changes in the subsidence of the basin during the Cenozoic.

SUGGESTED LOCATION OF FIGURE 11

4.3. Sea level changes

Several Cenozoic eustatic sea-level curves has been lately published (Miller et al., 2005; Komenz et al., 2008; Browning et al., 2008). All the proposal show a gradual, but consistent lowering of the sea-level since late middle Eocene, with an abrupt fall in the late Eocene **(Fig. 12A)**. The trend has been interpreted as a response to the expansion of ice on Antarctica (Miller et al., 1991; Browning et al., 1996). Other maine transgressions occurred close to the EOT **(Fig. 12B)** has been previosly identified in Argentina. In the Austral basin, the Cabo Peña Formation (Late Eocene-earliest Oligocene) contain cold-water dinoflagellate cysts (Guestein et al., 2002) that may be associated to the development of the Antarctic Circumpolar Current and the expansion of ice-sheets in Antarctica, which are also consistent with a lowering in eustatic sea-level. From this, a general scenario of low eustatic sea level is supported, strongly associated to the climate cooling vinculated to ice-house conditions (Kennet et al., 1977; Zachos et al., 2001; Sluijs et al., 2005; Houben et al., 2013). The general low eustatic scenario reinforce the importance of both extensional tectonics and flexural mechanisms associated to intrabasinal volcanism (commented above) as the likely explanation of the transgressive event that deposited the El Huemul Formation in the Golfo San Jorge Basin.

SUGGESTED LOCATION OF FIGURE 12

5. Conclusions

The El Huemul Formation is a lithostratigraphical unit preserved in the subsurface of the South Flank of the Golfo San Jorge Basin (Santa Cruz province). The unit is 80-110 m thick and cover continental tuffaceous deposits of the Sarmiento Formation, being subsequently covered by a marine succession containing *Cannosphaeropsis quattrocchiae*, a typical early Miocene (Burdingalian) dinoflagellate cyst, and other species that characterize the C/G dinoflagellate cyst assemblage zone of the Chenque Formation (early Miocene). From base to top, the El Huemul Formation consists of glauconitic sandstones with fining-upward log motif followed by mudstones and fine sandstones that coarsening upward, representing a single transgressive-regressive cycle. The El Huemul Formation contains *Gelatia inflata*, *Diphyes colligerum*, *Spiniferites scalenus* and *Tuberculodinium* sp. (of Guerstein *et al.*, 2008) together with *Reticulatosphaera actinocoronata*, an assemblage of dinoflagellate cysts that supports a late Eocene to early Oligocene (EOT) age for the unit.

Two main forcing factors may have contributed to preserve this unit in the South Flank of the basin. First, extensional reactivation of WNW-ESE to N-W striking faults during the

Paleocene-Eocene, which promoted mechanical subsidence prior to the transgression. The second mechanism is flexural isostatic subsidence associated to the incorporation and cooling of alkaline intrusive rocks in the Paleogene.

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Appendix I. Taxonomic list of palynomorphs recorded in the well SC.SIN.MEN-5024. Citations can be found in Fensome *et al*., 2004 except when indicated (*)

I.a. Dinoflagellate cysts

Batiacasphaera cf. *minuta* (Matsuoka 1983b) Matsuoka and Head, 1992

Brigantedinium simplex (Wall, 1965b) Lentin and Williams, 1993

Brigantedinium sp.

Cannosphaeropsis quattrocchiae Guerstein *et al.,* 2001

Cleistosphaeridum ancyreum (Cookson and Eisenack, 1965a) Eaton *et al.,* 2001

Cribroperidinium/Apteodinium spp.

Dapsilidinium pseudocolligerum (Stover, 1977) Bujak *et al.,* 1980

Diphyes colligerum (Deflandre and Cookson, 1955) Cookson, 1965a emend. Goodman and Witmer, 1985

Emmetrocysta urnaformis (Cookson) Stover, 1975

Habibacysta cf. *tectata* Head *et al.,* 1989b

Hystrichokolpoma rigaudiae Deflandre and Cookson, 1955

Hystrichosphaeropsis obscura Habib, 1972

Lejeunecysta spp.

Lingulodinium echinatum (*) (Menéndez, 1965) emend. Guerstein *et al.,* 2008

Lingulodinium hemicystum McMinn, 1991

Lingulodinium machaerophorum (Deflandre and Cookson, 1955) Wall, 1967

Melitasphaeriduim cf. c*hoanophorum* (Deflandre and Cookson, 1955) Harland and Hill, 1979

cf. *Malvinia escutiana* (*) Bijl *et al.,* 2011

Nematosphaeropsis sp. A

Operculodinium centrocarpum (Deflandre and Cookson, 1955) Wall, 1967

Reticulatosphaera actinocoronata (Benedek, 1972) Bujak and Matsuoka, 1986

Selenopemphix cf. dionaeacysta Head *et al*., 1989b

Spiniferites membranaceous (Rosssignol, 1964) Sarjeant, 1970

Spiniferites mirabilis (Rossignol) Sarjeant, 1970

Spiniferites ramosus (Ehrenberg, 1838) Mantell, 1854

Spiniferites scalenus (*) Guerstein *et al.*, 2008

Tuberculodinum sp. of Guerstein *et al.,* 2008

I. b.Green Algae

Prasinophyceae (*Tasmanites* sp.)

Hydrodictyaceae (*Pediastrum* sp.)

Apendix II. Other species cited in the text

II. a. Dinoflagellate cysts

Cannosphaeropsis utinensis Wetzel, 1933

II. b. Pollen

Baumannipollis chubutensis Barreda, 1993

Glencopollis ornatus Pocknall and Mildenhall, 1984

Margocolporites tenuireticulatus Barreda, 1997

Mutisiapollis patersonii Macphail and Hill, 1994

Tubulifloridites antipodica Cookson, 1947

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Figure Captions

Figure 1: (A) Location map of the study area. The stripped area indicates the maximum extension of the Early Miocene transgression in Patagonia (after Malumián *et al.*, 1999). **(B)** Main structural domains in the Golfo San Jorge Basin. The study area is located in the eastern sector of the basin (South Flank) where extensional tectonics prevails during the Cretaceous and Cenozoic. **(C)** Geological map of the Golfo San Jorge Basin.

Figure 2: (A) Study area, with location of regional cross sections presented in this work. The star indicates the well CS.SIN.MEN-5024 in Figure 4. **(B)** West-east well-log correlation showing the distribution of the Cenozoic record in the subsurface of the South Flank. Note the gradual thinning of most of the units toward the west and the occurrence of several normal faults affecting the sedimentary succession.

Figure 3: Typical well log and main subdivisions of the mid-Cenozoic marine record in the study area. SP= spontaneous potential, SB= sequence boundary, TST= transgressive system tract, HST= highstand system tract.

Figure 4: (A) Well log signature of the mid-Cenozoic marine succession based on information from the Well SC.SIN.MEN-5024, where palynological samples were obtained (location in Fig. 2). Field and laboratory sample numbers are indicated. Palynomorphs recorded in samples from the mud-logging in the Sarmiento Formation represent reworked specimens during the drilling. RT= resistivity log, SP= spontaneous potential **(B)** Mud-logging samples of well SC.SIN.MEN-5024. Boundary between cycles II and III can be

easily identified, but the lithological boundary between cycles I and II can be better defined using well logs.

Figure 5: Dinoflagellate cysts from the Chenque Formation. Specimens are identified by the slide number and the England Finder reference. Scale bare = 10 µm. **(A)** *Brigantedinium simplex* Sample 150a: C41-4. Dorsal view, upper focus. **(B-C)**. *Cannosphaeropsis quattrocchiae* Sample 150a: B40-0; B. Left lateral view, low focus; C. Left lateral view, upper focus. **(D)** *Hystrichokolpoma rigaudiae* Sample 150a: J42-4. Left lateral view, intermediate focus. **(E)** *Lejeunecysta* sp. Sample 150a: A32-3. Dorsal view, upper focus.**(F)** *Habibacysta* cf. *tectata* Sample 150a: X44-3. Dorsal view, upper focus. **(G-H)** *Lingulodinium hemicystum* Sample 150a: S42-2.; **(G)** Antapical view, upper focus; **(H)** Antapical view, lower focus **(I)** *Melitasphaeriduim* cf. *choanophorum* Sample 150a: C36-2, low focus. **(J)** *Operculodinium centrocarpum* Sample 195a: M18-0. Left lateral view, mid focus. **(K)** *Selenopemphix* cf. *dionaeacysta* Sample 165a: C23-3. Apical view, intermediate focus. **(L)** *Spiniferites mirabilis* Sample 150a: G51-2. Ventral view, intermediate focus.

Figure 6. Dinoflagellate cysts from the El Huemul Formation. Specimens are identified by the slide number and the England Finder reference. Scale bare = 10 µm. **(A)** *Batiacasphaera* cf. *minuta* Sample 270b: W31-1. Apical view, upper focus. **(B)** *Cleistosphaeridum ancyreum* Sample 270a: F53-0. Ventral view, low focus. **(C)** *Lingulodinium machaerophorum* Sample 270a: G41-0. Ventral view, upper focus. **(D-E)** *Emmetrocysta urnaformis* Sample 270a: C29-3. D. Ventral view, intermediate focus; E. Ventral view, upper focus. **(F)** *Gelatia inflata* Sample 270a: F37-2. Antapicical view, low

focus. **(G-H)** *Nematosphaeropsis* sp. A. G. Sample 270b: V43-2. Intermediate focus; H. Sample 270b: W27-4. Right lateral view, intermediate focus. **(I)** *Reticulatosphaera actinocoronata* Sample 270a: C53-0. Intermediate focus**. (J)** *Selenopemphix nephroides* Sample 270a: J46-1. Apical view, upper focus. **(K)** *Spiniferites scalenus* Sample 270a: M8-3. Apical view, lower focus on the internal antapical surface. **(L)** *Tuberculodinum* sp. (Guerstein *et al.*, 2008) Sample 255a: J35-0. Low focus on the processes with quadrangular cross-section and the fibroid ectophragm.

Figure 7: Semi-regional well-log correlations for the Cenozoic sedimentation in the study area. **(A)** South-north cross-section in the eastern part of the study area. **(B)** South-north cross-section in the type area of the El Huemul Formation**. (C)** South-north cross-section in the west of the study area. Location of cross-sections in Fig. 2. In D-D´cross-section the log signature differs from the eastern area and lithostratigraphical assignations are tentative; note that sedimentary packages display a layer-cake distribution. Key= Sa= base of Salamanca Formation; RC= base of Río Chico Group; S= base of Sarmiento Formation; EH= base of El Huemul Formation (Cycle I); CH= base of Chenque Formation (Cycles II and III) are indicated in cross-sections B-B´and C-C´.

Figure 8: (A) Structural map of the base of the El Huemul Formation. Note the shift in the dominant orientation of the contour lines evidencing the main orientation of the mid-Cenozoic normal faults of the study area. Topography of the model surface is shown using contour lines at 20 m intervals. **(B)** Thickness distribution of the El Huemul Formation (*nov. denom*.) in the subsurface of the study area. Contour lines at 10 m intervals.

Figure 9: (A) Structural map of the base of the Chenque Formation (lower Miocene). Contour lines every 10 meters. **(B)** Thickness map of the Chenque Formation. As the unit reaches the surface in most of the area, its preserved thickness is mainly controlled by the intensity of the post-depositional erosional processes. Contour lines= 20 meters.

Figure 10: Paleocene-Eocene extensional tectonics in the South Flank. **(A)** Location of sections. **(B)** High-angle normal faults with block rotations in the Salamanca Formation and Río Chico Group. **(C)** Seismic section of the eastern part of the study area illustrating several high-angle normal faults with large displacements in the Salamanca and Río Chico Group. Notice thickness variation of the Sarmiento Formation along the section.

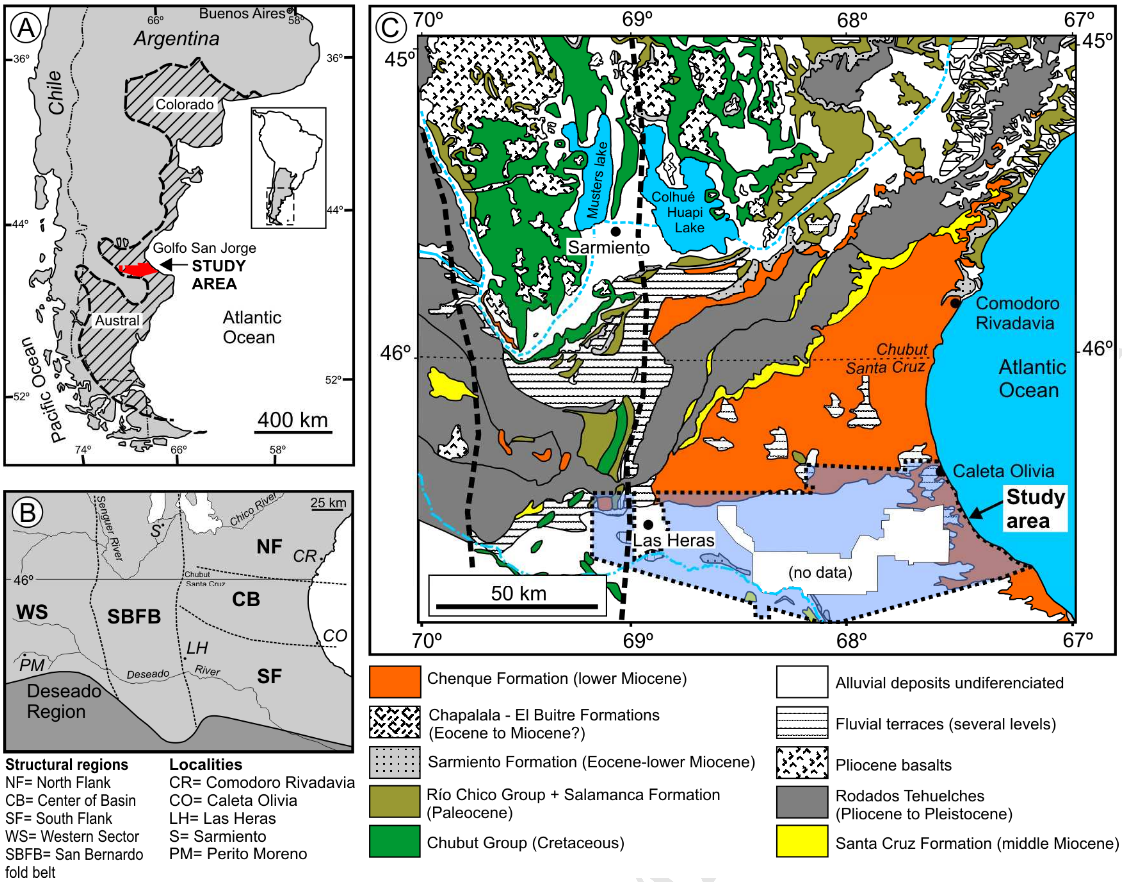
Figure 11: Seismic expression of intrusive rocks and dike systems. Location in Figure 10. **(A)** Horizontal slice (1300 msec TWT, near the base of Meseta Espinosa Formation) through a variance attribute volume, without interpretation. **(B)** Interpreted horizon slice. Red circles indicate the approximate location of vertical conducts of the intrusives, dotted lines are sub-vertical dykes. Two elliptical shapes in the center of the image (light grey shading) resemble the emplacement of intrusives at this depth. W-E and WNW-ESE normal faults of the area were omitted for clarity.

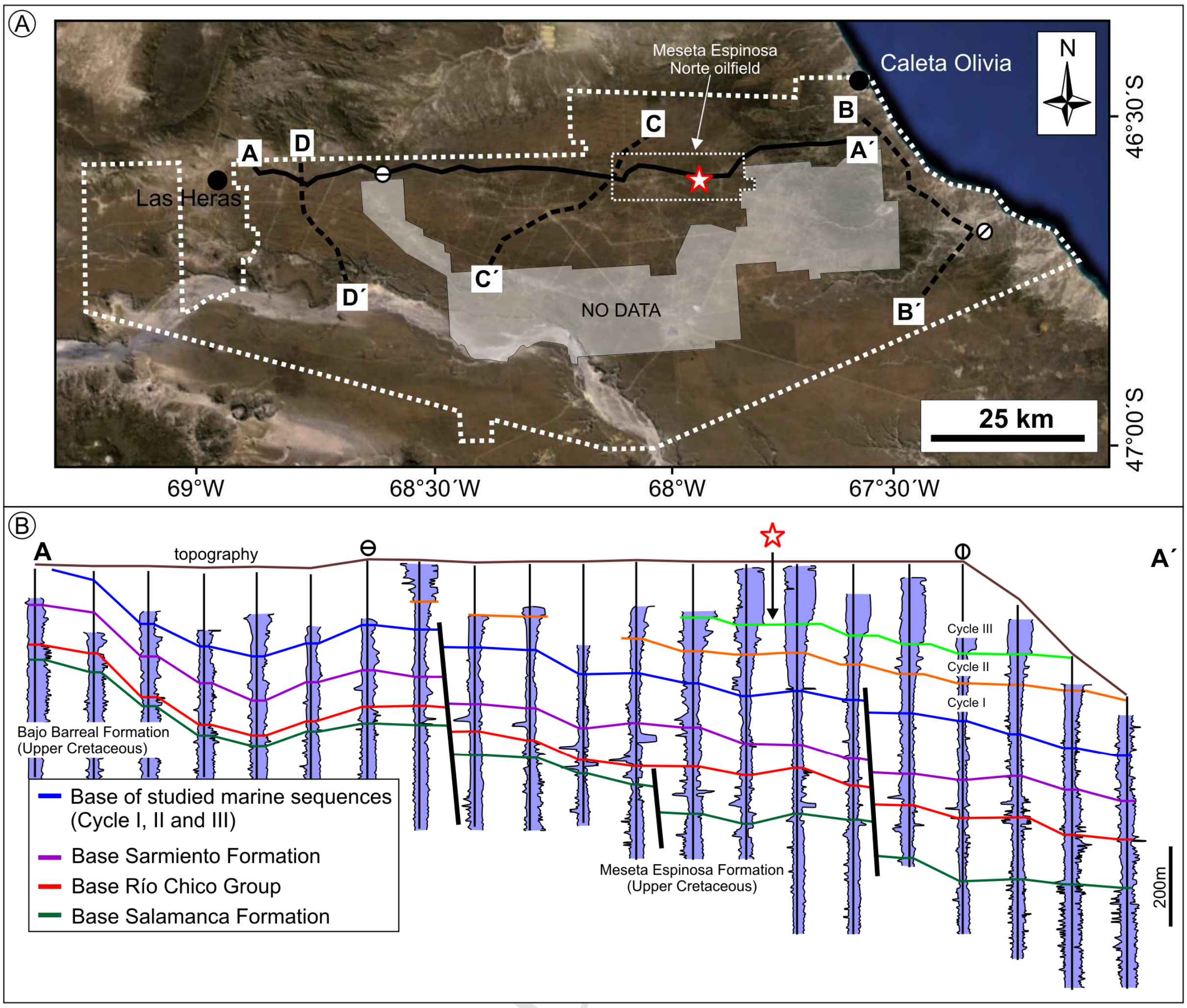
Figure 12: (A) Eustatic sea-level variations since the Eocene, after Miller et al. (2005). Note the slightly lowering in sea-level from middle Eocene, and the approximate age obtained for the El Huemul Formation based in dinoflagellate cysts. **(B)** Simplified paleogeographic sketch with indication of the coeval marine units preserved in the

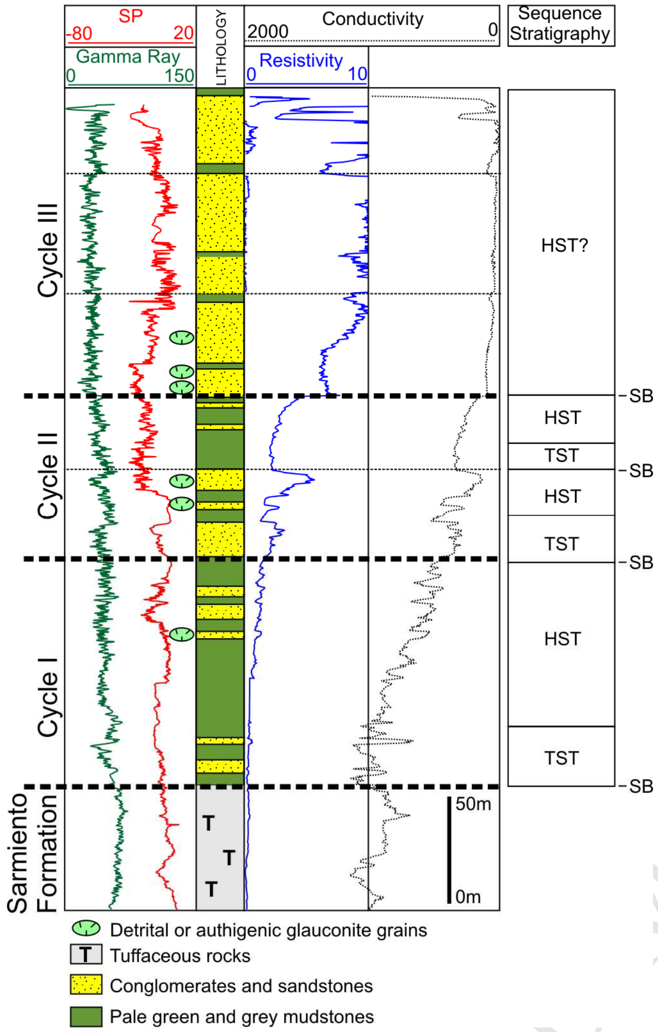
Colorado, Golfo San Jorge and Austral basins around the EOT (after Malumián et al., 1999).

Table I. Stratigraphic distribution of dinoflagellate cyst taxa and number of specimens recoel frded in the well SC.SIN.MEN-5024, plotted against depth and lithostratigraphical units.

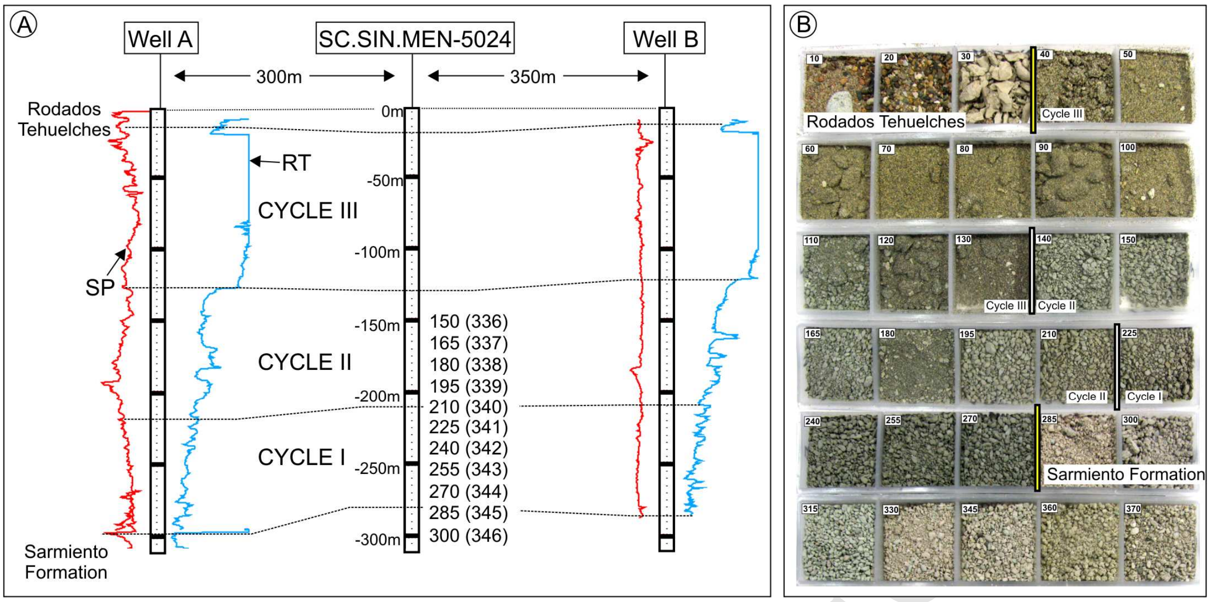
ERA	EPOCH	LITOSTRATIGRAPHICAL UNITS	BIOZONES Barreda and Palamarczuk (2000)	DEPTH (metres)	SAMPLES	*Brigantedinium* spp.	*Cannosphaeropsis quattrocchiae*	*Habibacysta* cf. *tectata*	*Hystrichokolpoma rigaudiae*	*Lejeunecysta* spp.	*Melitasphaeridium* cf. *choanophorum*	*Operculodinium centrocarpum*	*Operculodinium* spp.	*Selenopemphix dionaeacysta*	*Selenopemphix nephroides*	*Spiniferites membranaceous*	*Spiniferites ramosus*	*Spiniferites* spp.	*Lingulodinium machaerophorum/hemicystum*	*Selenopemphix* spp.	*Dapsilidinium pseudocolligerum*	*Reticulatosphaera actinocoronota*	*Cribroperidinium/Apteodinium* spp.	*Emmetrocysta urnaformis*	*Gelatia inflata*	*Clesitosphaeridium ancyreum*	*Nematosphaeropsis* sp. A	*Spiniferites mirabilis*	*Tuberculodinium* sp. of Guerstein et al., 2008	*Cleistosphaeridium placacanthum*	*Diphyes colligerum*	cf. *Malvinia escutiana*	*Spiniferites scalenus*	*Lingulodinium echinatum*	*Pediastrum* sp.	Prasinophyceae	Foraminifera linings
CENOZOIC	EARLY MIOCENE	CHENQUE FORMATION	G/C	150	336	4	10	1	1	2	1	8	10	1	1	1	2	4																		2	2
				165	337	1	4			4			1				3	3	1	2																	4
				180	338	1	5			3		2	9				3	11		1	1	2													1	2	3
				195	339		8		2			10						17																		28	
				210	340		6		5			2	5					13	1			11	3													5	1
	?		?	225	341								4				1	3																			2
	EOCENE - OLIGOCENE TRANSITION	EL HUEMUL FORMATION		240	342		3C						9			5	10	3	3	2	3	6	1	14	3												5
				255	343		2C			43		19	15		20	4		48	34	14		48	1		5	6	2	3	1								28
				270	344					23		45	23		5	7	2	58	5	1		40		1	4	11	18	2	2	3	1	1	1			1	32
				285	345					2		15	26					16	2		1	6				1								3			3
				300	346							7	1					5	3																		
		SARMIENTO FORMATION		315	347	Barren of palynomorphs																															
				330	348																																
				345	347																																
				360	348																																

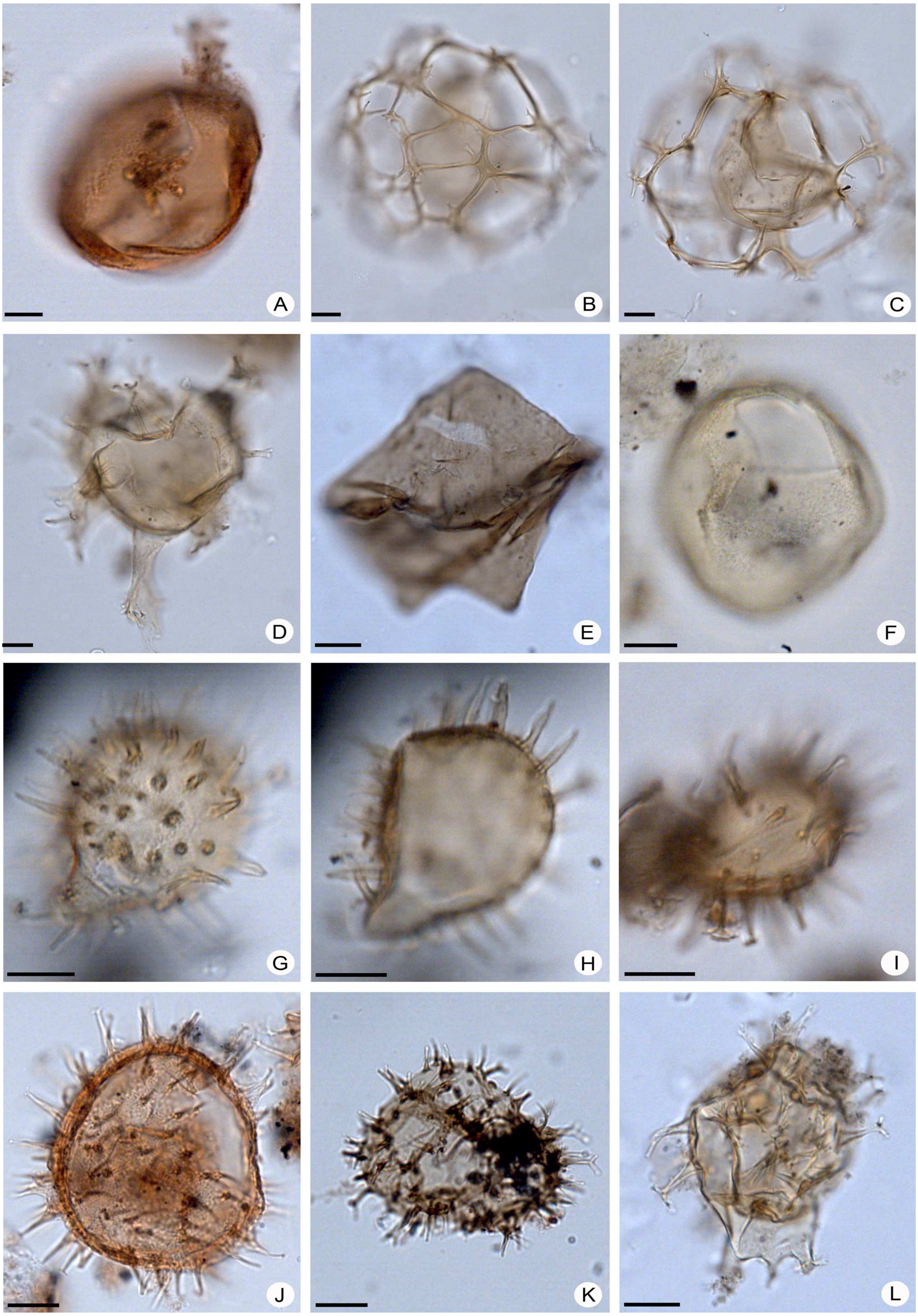

A
Buenos Aires
Argentina
Chile
Colorado
Golfo San Jorge
STUDY AREA
Austral
Atlantic Ocean
Pacific Ocean
400 km
36º
44º
52º
74º
66º
58º
B
25 km
Senguer River
Chico River
S
NF
CR
46º
Chubut
Santa Cruz
WS
SBFB
CB
CO
LH
PM
Deseado
River
SF
Deseado Region
Structural regions
NF= North Flank
CB= Center of Basin
SF= South Flank
WS= Western Sector
SBFB= San Bernardo fold belt
Localities
CR= Comodoro Rivadavia
CO= Caleta Olivia
LH= Las Heras
S= Sarmiento
PM= Perito Moreno
C
70º
69º
68º
67º
45º
46º
Musters lake
Colhué Huapi Lake
Sarmiento
Comodoro Rivadavia
Chubut
Santa Cruz
Atlantic Ocean
Caleta Olivia
Study area
Las Heras
(no data)
50 km
Chenque Formation (lower Miocene)
Chapalala - El Buitre Formations (Eocene to Miocene?)
Sarmiento Formation (Eocene-lower Miocene)
Río Chico Group + Salamanca Formation (Paleocene)
Chubut Group (Cretaceous)
Alluvial deposits undiferenciated
Fluvial terraces (several levels)
Pliocene basalts
Rodados Tehuelches (Pliocene to Pleistocene)
Santa Cruz Formation (middle Miocene)

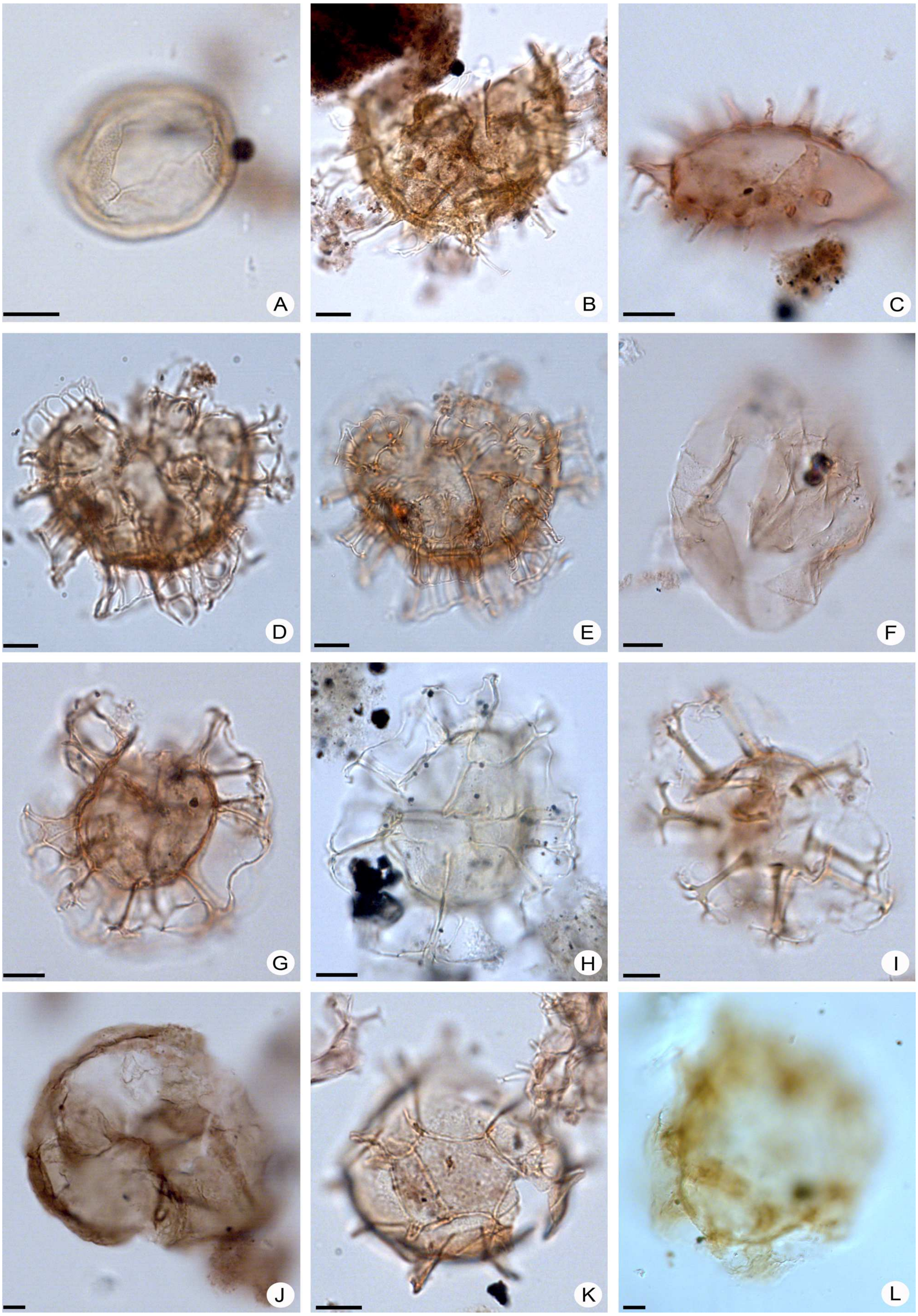

A
Meseta Espinosa
Norte oilfield
Caleta Olivia
N
B
C
A
D
A´
Las Heras
C´
D´
NO DATA
B´
25 km
46°30´S
47°00´S
69°W
68°30´W
68°W
67°30´W
B
A
topography
A´
Cycle III
Cycle II
Cycle I
Bajo Barreal Formation
(Upper Cretaceous)
Base of studied marine sequences
(Cycle I, II and III)
Base Sarmiento Formation
Base Río Chico Group
Base Salamanca Formation
Meseta Espinosa Formation
(Upper Cretaceous)
200m

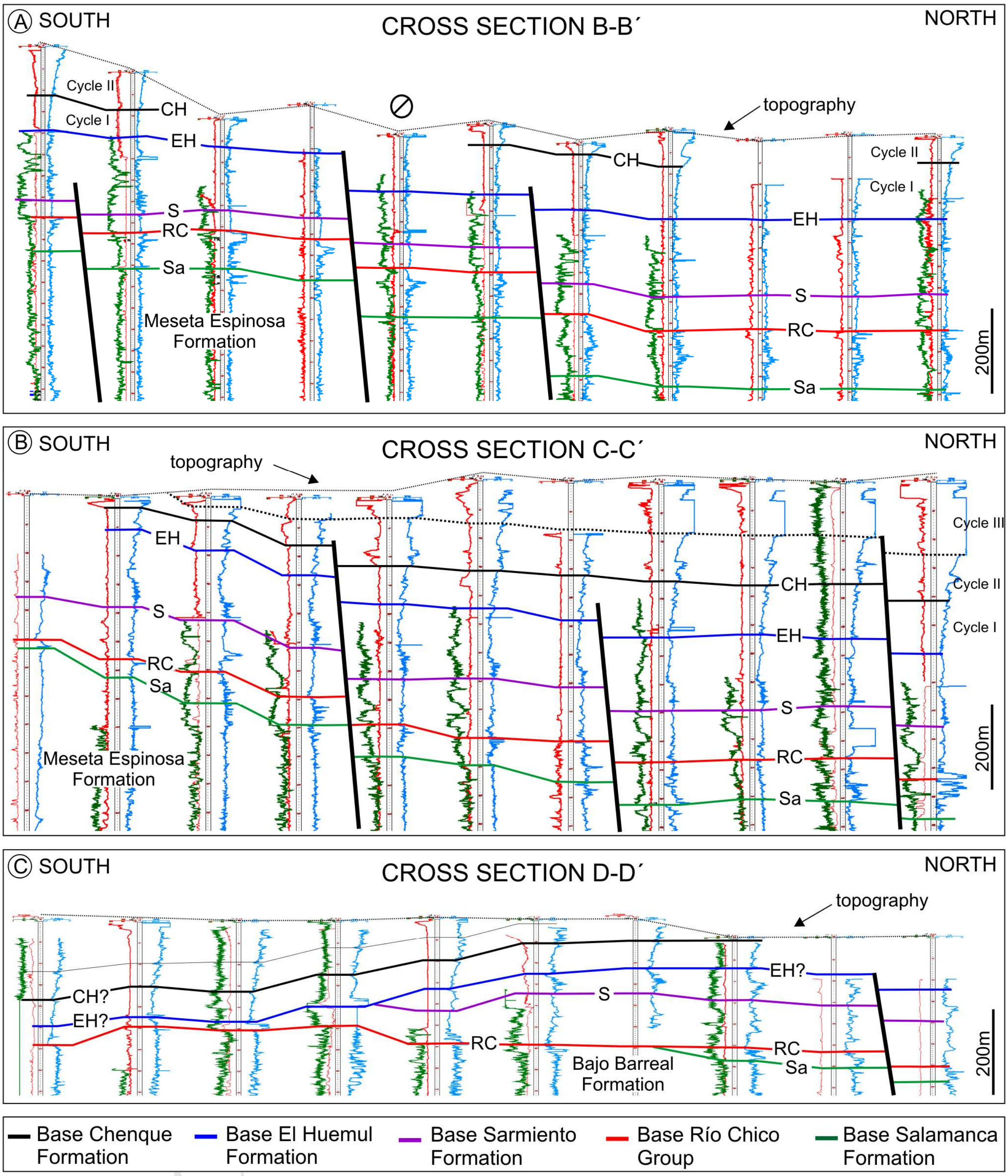


SP
-80
20
Gamma Ray
0
150
LITHOLOGY
Conductivity
2000
0
Resistivity
0
10
Sequence Stratigraphy
Cycle III
Cycle II
Cycle I
Sarmiento Formation
HST?
HST
TST
HST
TST
HST
TST
SB
SB
SB
SB
T
T
T
50m
0m
Detrital or authigenic glauconite grains
Tuffaceous rocks
Conglomerates and sandstones
Pale green and grey mudstones

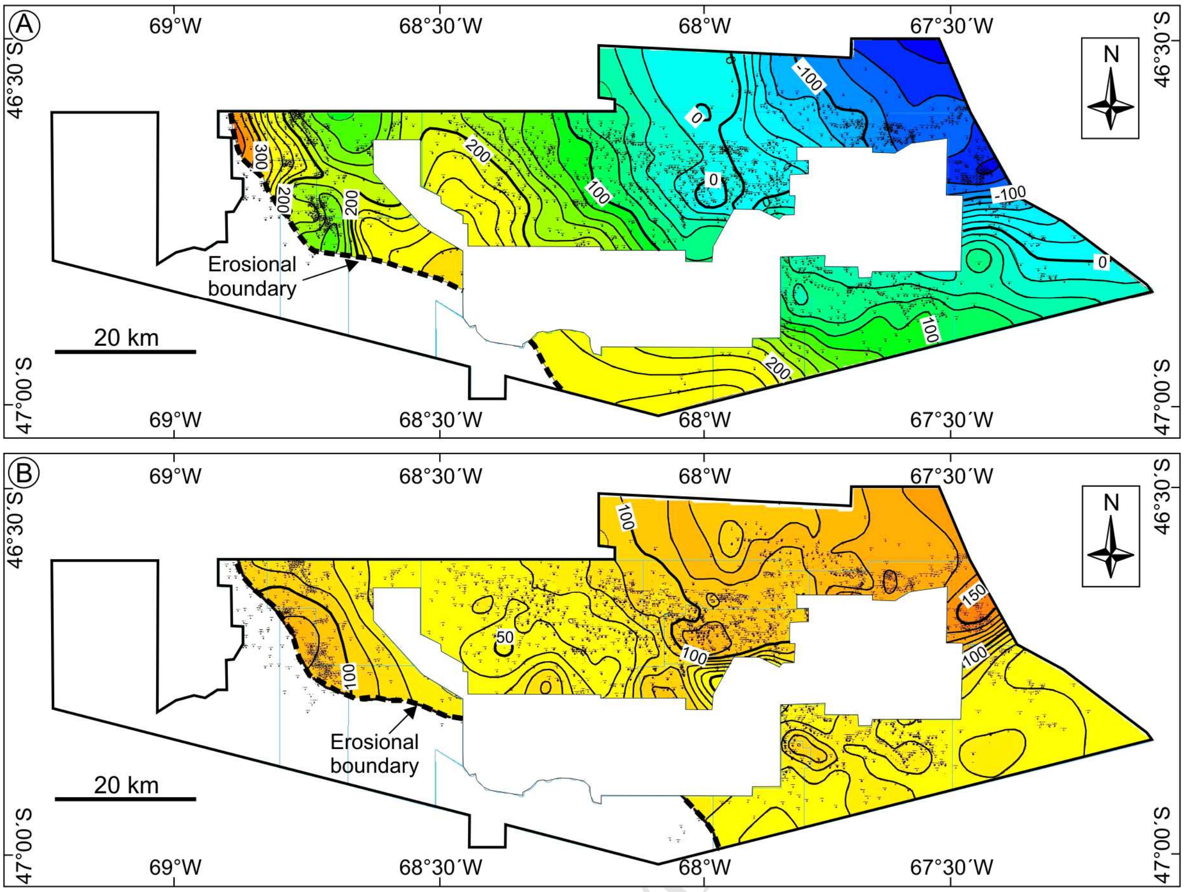

A
Well A
SC.SIN.MEN-5024
Well B
300m
350m
Rodados
Tehuelches
0m
-50m
-100m
-150m
-200m
-250m
-300m
RT
CYCLE III
CYCLE II
CYCLE I
SP
Sarmiento
Formation
150 (336)
165 (337)
180 (338)
195 (339)
210 (340)
225 (341)
240 (342)
255 (343)
270 (344)
285 (345)
300 (346)
B
Rodados Tehuelches
Cycle III
Cycle II
Cycle I
Sarmiento Formation
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
165
180
195
210
225
240
255
270
285
300
315
330
345
360
370

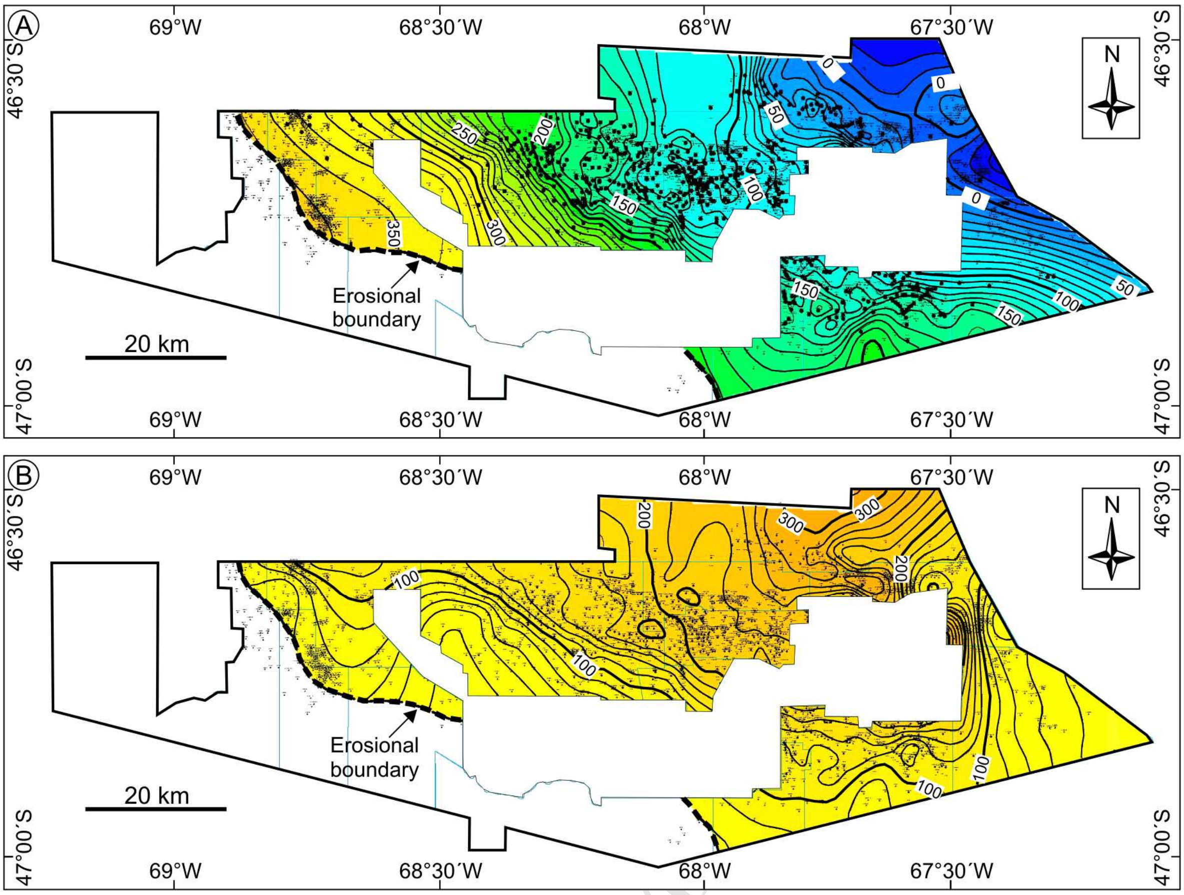

A
B
C
D
E
F
G
H
I
J
K
L

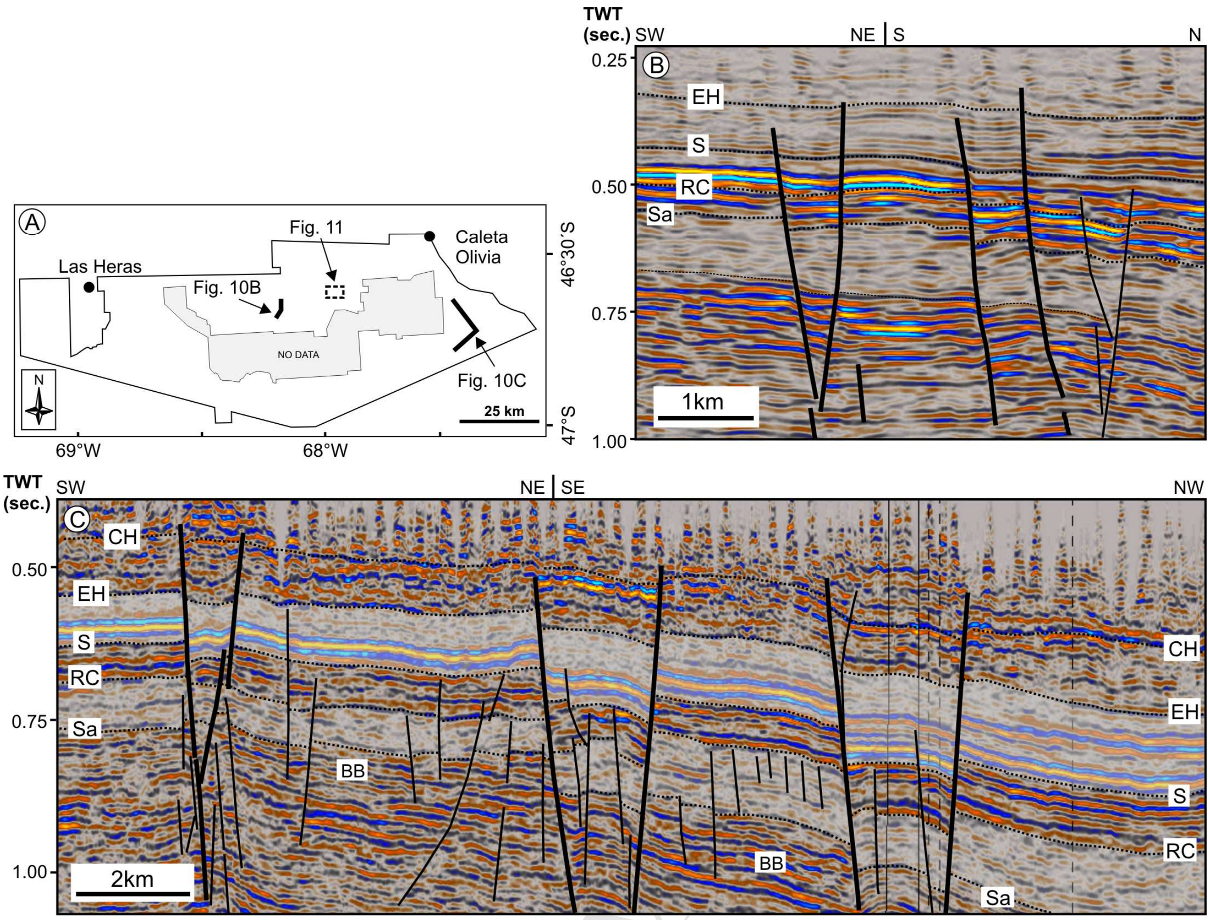

A
B
C
D
E
F
G
H
I
J
K
L

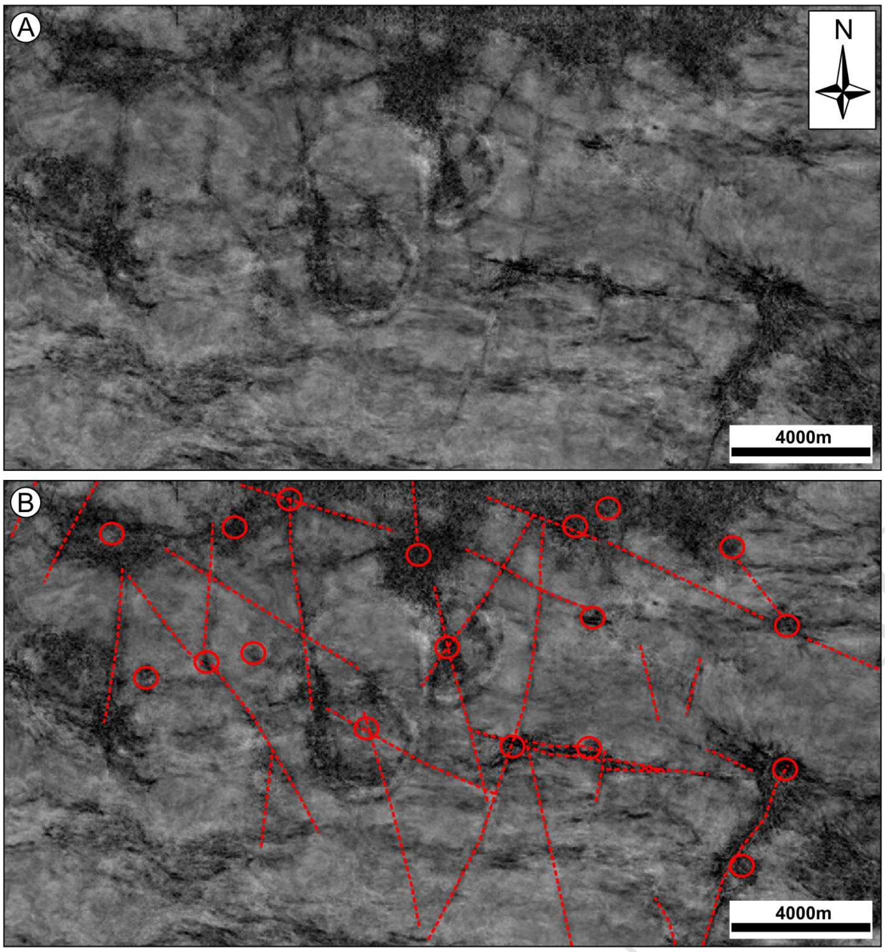


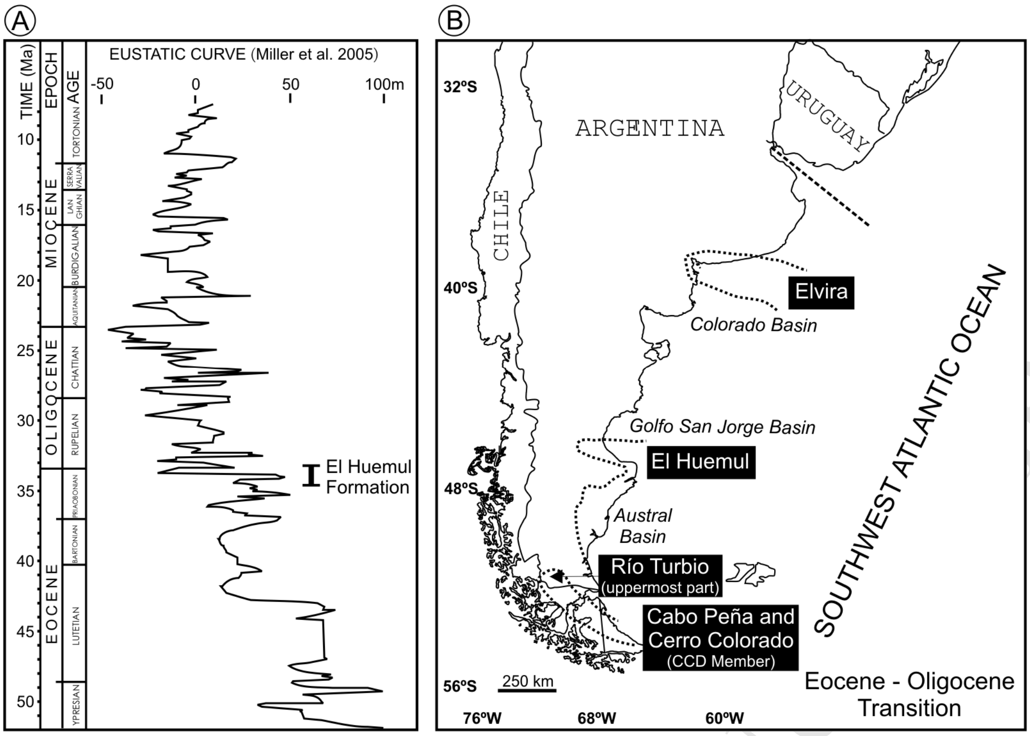
A SOUTH
CROSS SECTION B-B´
NORTH
Cycle II
Cycle I
CH
EH
topography
S
RC
Sa
Meseta Espinosa Formation
200m
B SOUTH
CROSS SECTION C-C´
NORTH
topography
Cycle III
Cycle II
Cycle I
Meseta Espinosa Formation
C SOUTH
CROSS SECTION D-D´
NORTH
CH?
EH?
Bajo Barreal Formation
Base Chenque Formation
Base El Huemul Formation
Base Sarmiento Formation
Base Río Chico Group
Base Salamanca Formation


A
69°W
68°30´W
68°W
67°30´W
46°30´S
47°00´S
N
300
200
200
200
100
0
0
-100
-100
0
100
200
Erosional
boundary
20 km
B
100
150
100
50
100
100
Erosional
boundary
20 km


A
69°W
68°30´W
68°W
67°30´W
46°30´S
47°00´S
N
Erosional boundary
20 km
B


A
Las Heras
Fig. 11
Caleta Olivia
Fig. 10B
NO DATA
Fig. 10C
25 km
N
46°30'S
47°S
69°W
68°W
B
TWT (sec.)
SW
NE
S
N
0.25
0.50
0.75
1.00
EH
S
RC
Sa
1km
C
TWT (sec.)
SW
NE
SE
NW
0.50
0.75
1.00
CH
EH
S
RC
Sa
BB
BB
2km


A
N
4000m
B
4000m



A
TIME (Ma)
EPOCH
AGE
EUSTATIC CURVE (Miller et al. 2005)
-50
0
50
100m
MIOCENE
OLIGOCENE
EOCENE
TORTONIAN
BURDIGALIAN
CHATTIAN
RUPELIAN
LUTETIAN
YPRESIAN
El Huemul Formation
B
ARGENTINA
URUGUAY
CHILE
32ºS
40ºS
48ºS
56ºS
Elvira
Colorado Basin
Golfo San Jorge Basin
El Huemul
Austral Basin
Río Turbio
(uppermost part)
Cabo Peña and Cerro Colorado
(CCD Member)
SOUTHWEST ATLANTIC OCEAN
250 km
Eocene - Oligocene Transition
76ºW
68ºW
60ºW

A non-previously identified transgressive event of late Eocene- early Oligocene age was identified in the subsurface of the Golfo San Jorge Basin.

A dinoflagellate cysts assemblage containing *Gelatia inflata*, *Diphyes colligerum* and *Reticulatosphaera actinocoronata* constrains the age of the marine incursion.

A new lithostratigraphical unit is proposed: the El Huemul Formation. The unit consists of a thin lag of glauconitic sandstones with fining-upward log-motif, followed by a mudstone-dominated succession that coarsening-upward to sandstones, evidencing a full T-R cycle.

Extensional tectonics and flexural loading associated to alkaline intrusives of Paleogene age were responsable for the generation of accommodation space prior to the transgression.